STANDARDS FOR RESPONSIVE SMALL SATELLITES

Gurpartap S. Sandhoo[1], Aaron Q. Rogers[2], Patrick. A. Stadter[2], Eric Finnegan[2], Michael Hurley [1], Mark Johnson[1], William Raynor[1], Paul. D. Schwartz [2], LTCOL James Griswold, USAF [3]

[1] *Naval Research Laboratory, 4555 Overlook Ave, SW, Washington, DC, 20375 USA, Email: gurpartap.sandhoo@nrl.navy.mil*
[2] *The Johns Hopkins University/Applied Physics Laboratory, Laurel, MD, 20723 USA, Email: aaron.rogers@jhuapl.edu*
[3] Rapid Reaction Technology Office, Department of Defense R&E Washington, DC, USA, Email: james.griswold@osd.mil

ABSTRACT

The U.S. Naval Research Laboratory and The Johns Hopkins University/Applied Physics Laboratory are collaborating with a large industry team of partners to develop, mature, and document standards for small spacecraft systems as part of the Operationally Responsive Space (ORS) Phase III effort. Under the subsequent Phase IV, the newly formed ORS joint program office will utilize these standards and other collected lessons learned to aid development of strategic roadmaps and eventual system acquisitions. Currently, an NRL/APL team is working to develop a prototype spacecraft bus to implement and mature key elements of the standards while additionally supporting the requirements and CONOPS of the TacSat-4 mission. This paper will discuss the approach used in developing the ORS bus standards, including how performance thresholds were established and, in detail, the iterative application, and maturation of those standards through the practice of building an actual flight system. Particular emphasis will be placed on addressing these and related topics that are within the scope of the ORS enterprise. A brief discussion of the system designed and built for the TacSat-4 mission will follow.

1. INTRODUCTION

1.1. Background

The Department of Defense under the guidance of the Office of Force Transformation (OFT) sought to develop new revolutionary operational concepts and technologies for the conducting military operations. This vision embraces two fundamental elements to provide responsive capabilities to the Warfighter by leveraging space assets: (1) operational systems that can be quickly deployed to meet tactical Warfighter needs, and (2) science and technology (S&T) systems that use rapidly developed, cost-effective standard systems to develop new technologies through experimentation. To date much of the focus of individual programs has been on developing S&T systems that attempt to provide a spiral development capability towards operational systems that will be components of an Operational Responsive Space (ORS) acquisition. The DoD vision hopes to bridge the gap between S&T systems and operational systems by using aspects of the S&T experiments as inputs to future operational systems.

It should be noted that there are other critical element of the ORS concept, namely responsive launch, range operations, and space operations centers. These efforts are also the focus of several initiatives. The success of these efforts is essential to the success of any ORS system. The Standard Bus Initiative is the focus of this paper.

1.2. OFT ORS Program Summary

As the several responsive space efforts begun to better coordinate efforts toward the common goal of providing new capabilities to the tactical Warfighter and disadvantaged user, one common need that emerged was a desire to move towards more standardized systems. A fundamental reason for this is the drive for a successful acquisition of both operational and S&T systems – standardization at a system level, developed in partnership among government, industry, and academia, allows for broader, more competitive acquisitions and would provide a healthier industrial base.

The need for effective spacecraft bus standards has been broadly identified as a necessary condition for a successful ORS system. Therefore this ORS Bus Standards Initiative was undertaken.

The OFT and SMC undertook a four phase initiative to develop and test bus standards and subsequently transition them to acquisition. This effort involves multiple government laboratories, industry partners, and academic institutions.
The four phases (*Figure 1*) of this initiative provide steady, tangible steps to spiral capability and receive operational feedback while moving toward the final goal of a successful DoD acquisition for both operational and S&T systems.

Phase I provided initial analysis of a technical framework for ORS systems, utility, the business case

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,and related elements of these systems. It encompassed the potential of a broader user community than just the DoD, including civilian uses. Phase II is an AFRL effort that is focusing on the rapid development of a specific bus to meet the TacSat-3 mission while advancing, within programmatic constraints, avionics standards between the bus and the payload. The Phase III effort, as detailed herein, is a joint NRL/APL effort, with significant industry and academic participation, to develop a sustainable spacecraft bus standard that will serve elements of future acquisitions (e.g., one of several classes of ORS buses) and to prototype a standard bus to vet that developed standard. Phase IV of the Initiative, represents the fundamental goal of all parties – the acquisition of operational ORS systems to provide new tactical capabilities to the Warfighter and disadvantaged users.

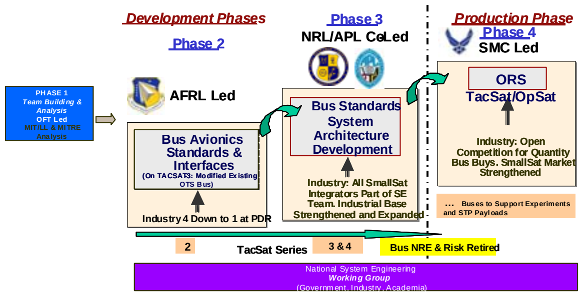

Figure 1: Four Phases of Bus Standards Effort

A more detailed description of the various phases follows.

1.3. Phase I – Analysis and Business Case

Phase I consisted of two focused studies to analyze the technical and business aspects of a standard bus within the ORS System concept. The thrust of the business case effort, led by MITRE, was to consider the broader user community of bus standards and the potential for overall acquisition from industry of a standard bus from the classes under consideration for ORS.

The second element of the Phase I effort was led by MIT/Lincoln Laboratory (MIT/LL) and focused on developing a technical framework for classes of ORS standard buses in an effort to assess their utility within the identified mission context. The research sought to determine whether meaningful military utility could be realized from relatively small spacecraft. This phase provided an analytical departure point to determine at least one proper class of ORS spacecraft needed to be militarily relevant. This utility analysis drew on experienced users and system developers to generate measures of utility mapping system characteristics (e.g., geolocation accuracy, imaging resolution, dwell time, etc.) to mission capability across a broad set of identified ORS mission areas. Missions considered included RF collection, visible imaging, spectral imaging, navigation, communications, etc. [1]

Phase I analysis from the Massachusetts Institute of Technology/Lincoln Laboratories (MIT/LL) identified over fifteen performance metrics such as resolution, target location error, sensitivity, frequency range, etc. within ten mission areas. Mission area examples include RF collection, visible imaging, spectral imaging, navigation, and communications. The utility of each performance metric and the weighted value of that metric were determined and entered into a systems-of-systems model. The parametric tool used spacecraft design models to determine spacecraft bus performance characteristics such as size, weight, power, communications, etc. for approximately 120,000 varying bus designs and then evaluated the overall military utility for each design as well as the relative cost in order to plot the trend of utility versus cost. Based on the results of the utility analysis, the report had several findings.

First, a tactical spacecraft bus, standardized across variety of National Security Space (NSS) missions, can meet many, but not all needs of a tactical commander. Second, small sized tactical satellites can achieve large increases in mission utility if used in constellations to improve persistence. Lastly, there exist standard performance specifications for a small tactical satellite bus that satisfy a wide range of NSS missions. **Error! Reference source not found.** shows a summary of varying performance characteristics for the type of spacecraft bus required for an ORS system, depending on the overall optimization goals or design limits imposed. Each column presents the results for a single spacecraft and show that actual ORS spacecraft characteristics should not be less than presented or they will not be useful. In addition, ORS spacecraft characteristics should not be much more or they will break the low cost and responsiveness model.

1.4. Phase II-Modular Bus Development

The Phase II bus effort is led by AFRL. This phase has two required objectives: provide avionics standards between the bus and the payload and provide a spacecraft bus for the TacSat-3 hyper spectral payload. In addition, many other approaches to internal bus modularity and plug-and-play bus standards are being explored in this phase.

It is expected that some of the external interfaces with the spacecraft will be brought to maturity by the Phase II development effort and will subsequently be captured within the Phase III Bus Standards development effort or in Phase IV. The development of the Phase II Modular bus provided technical, performance, and cost inputs and lessons which were factored into the resulting ISET standards for Phase III.

Table 1: Phase I ORS Bus Characteristics:

	Max Utility, "Low" Cost	400 kg Limit	250 kg Limit	Max Utility / Cost	Units
PL Power	250.0	200.0	100.0	250.0	W
PL Mass	200.0	150.0	100.0	100.0	kg
DL Rate	50.0	50.0	50.0	10.0	MBps
Num Orbits	12.0	8.0	3.0	12.0	#/day
Point Know	10.0	10.0	10.0	10.0	Arc-s
Point Control	40.0	40.0	60.0	60.0	Arc-s
Slew Rate	10.0	10.0	10.0	10.0	Deg/min
Mission Life	2.0	2.0	2.0	2.0	Yrs
PL Duty	0.2	0.5	0.2	0.2	Fraction
DL Band	7.5	7.5	7.5	7.5	GHz
Max DV	500.0	100.0	0.0	100.0	m/s
Total Mass	566.8	378.1	238.4	264.7	kg
Bus Mass	366.8	228.1	138.4	164.7	kg
Bus Dry Mass	288.7	216.2	137.8	156.4	kg
Avg Power	183.6	228.7	140.9	166.2	W
Peak Power	432.8	411.2	249.5	414.4	W
Array Area	1.1	1.4	0.9	1.0	m2
Bat Capacity	306.2	381.1	234.1	276.9	W-hr
Total Volume	0.4	0.3	0.2	0.3	m3

1.5. Phase III- Bus Standards

Phase III objectives are to develop and mature bus standards in an open environment with broad government, industry, and academia participation. This was accomplished by forming a national system engineering working group with the US small satellite industry to establish and maintain ORS bus standards to include both technical and business factors. Several methods of participation and contracting mechanisms were used by the government-industry team to facilitate the development approach. There was early realization in the Phase III effort that the setting of standards for a spacecraft bus was inseparable from the procurement volume, rate, and other business factors. To explore and validate the standards, prototyping a bus with ORS system-level standards was conducted to retire nonrecurring engineering (NRE) with government investment, and provide a credible baseline for the Phase IV acquisition.

The phase III effort produced several development documents, including a Payloads User's Guide, which will support the Phase IV team by providing guidance to payload developers that wish to take advantage of the ORS Bus Standards – this can serve as a "requirements document" to vendors developing payloads for flight within the ORS enterprise. In addition Phase III developed a set of "Bus Standards" documents that will be used as a "requirements document" to vendors developing spacecraft for the ORS program.

The Phase III effort provides a Prototype Vehicle used to vet the process and the standards. Lessons learned throughout the duration of the Phase III effort will be iteratively leveraged to improve and update the bus standards and processes used during Phase IV. The prototype bus developed under this effort will be integrated with a COMM-X payload in Fall 2008 for the TacSat-4 mission.

1.6. Phase IV- Spacecraft Acquisition

The Phase IV bus acquisition is led by ORS Office, the results of Phase III will help form the basis for standards and provide a credible baseline for this procurement.. Relative to industrial and production aspects of the ORS program, the Business Team developed a Transition Plan that provides a roadmap for the procurement of satellites and continued evolution of standards. As payloads are acquired, waivers to the standards will be addressed on a case-by-case basis. In many cases, waivers can be granted with no impacts once the specifics of a payload and mission are understood. If such as waiver would require bus modifications, the acquiring organization will need to determine if the payload or mission is worth the modification or whether to exclude such as payload if bus modification is deemed to costly or to have further ORS system impacts.

2. ORS PHASE III BUS STANDARDS

The primary product of the Phase III effort is a set of bus standards, including a Payload User's Guide, allowing payload designers to design to the ORS standard bus. This guide, combined with some volume procurement in Phase IV, could begin a fundamental change in bus-payload user interactions and approach. The second product is a bus "design specification" that will contain the developed standards, interfaces, and overall performance level (slew rate, power, mass, etc.) of the spacecraft bus, including data protocols and launch vehicle interface details. While this collection of items could be considered the bus "standard," it is important to realize that this is not a spacecraft point-design, nor does it represent a design that is imposed on industry; but instead a system-level performance and interface specification that will enable multiple developers and integrators to support future acquisitions as described in the transition plan. Finally, a prototype bus for flight experimentation was produced. While Phase III will provided a single bus for flight experimentation, success will be determined by the transition to ORS office for quantity procurements.

2.1. Integrated System Engineering Team (ISET)

Recognizing that significant buy-in from the industry was necessary to construct a set of standards that govern the design, manufacturing, assembly, test and integration of a high utility bus, the concept of an Integrated Systems Engineering Team (ISET) was established. The basic charter of this team is to develop a set of specific standards that allow industry to produce spacecraft buses for the government at moderate volume for low cost that provide, on average, the "80% utility" solution across a number of mission types. To establish the team, the government solicited responses from credible domestic small satellite integrators to supply senior systems engineering support to both high-level architecting activities, as well as detailed subsystem evaluation. Representatives had demonstrated hands on experience in the design, development, manufacturing, integration, and test of satellites, preferably small satellites, and/or volume production of satellites.

The ORS Phase III Bus Standards effort began with an industry day briefing on March 31, 2005 at the Naval Research Laboratory. The Air Force Research Laboratory (AFRL), Space & Missile Systems Center (SMC) Det-12, NRL, and APL gave briefings. US small satellite integration companies were encouraged to submit proposals to participate in the ISET. Proposal evaluation was conducted in early May 2005.

The proposal selection criteria focused on small satellite companies who are established small satellite integrators with flight hardware build experience within the last ten years. The companies selected were Swales (now ATK), AeroAstro, Design-Net, Microcosm, Space Systems/Loral, General Dynamics-Spectrum Astro, Microsat Systems Incorporated, Boeing, and Raytheon. Space Dynamics Lab (SDL) was also later selected to participate as a payload consultant to the ISET.. The first ISET meeting was held at JHU/APL on June 3, 2005.

2.2. Bus Standards Vs Standard Bus

The starting point for the ISET was a review and understanding of the results of the Phase I study. With this basis, at the first deliberation session, the ISET adopted the following charter:

"Generate a set of spacecraft bus standards, in sufficient detail to allow a space vehicle manufacturer to design, build, integrate, test and deliver a low cost spacecraft bus satisfying an enveloping set of mission requirements (launch vehicle, target orbit, payload, etc) in support of a tactical operational responsive space mission."

From this charter, the ISET identified four objectives and goals to achieve in support of tactical ORS missions. First, the team would extract from the MIT/LL study and other resources a top level set of mission requirements and concept of operations for ORS spacecraft. Second, the external interfaces of a standard spacecraft bus would be identified and standards established for each of those interfaces. As much as possible, the ISET would stay away from defining the internal interfaces within the spacecraft. Individual spacecraft designers and manufacturers would be free to define those elements consistent with their own specific spacecraft design practices. Third, the functional and performance standards for the standard spacecraft bus must be established. Fourth, in specific support of Phase IV acquisition activities, the ISET must establish programmatic mission assurance and quality assurance recommendations.

It was necessary to record the focusing assumptions and constraints the ISET would accept before drafting the standards.

First, in order to support tactical operational responsive space, the mission envelopes and spacecraft support identified must consider tasking and data dissemination to the theatre, but limited to the theatre command level.

The second assumption was that, when "standard" spacecraft buses go into production, the "Nth" item goal for production costs would be approximately $5 to $25 million dollars and the production volume requested by the procuring agency would be at least five spacecraft per year on a perpetual basis. The intent being to regularly launch ORS buses and payloads in response to crises, for TacSat experiments, and/or to maintain operational readiness.

The third assumption was that the standard spacecraft buses, in addition to payloads, will be procured in advance of needs and stored in pre-positioned integration facilities. Responsiveness would be achieved at the mission level. The timeline from payload/spacecraft bus integration to operational use, including payload integration, launch processing, and on-station checkout should be less than seven days. This was chosen to be consistent with timescales associated with Air or Space Tasking Orders (A/STO). Keeping the bridge to the AFRL-led ORS Phase II development activities, the ISET would consider architectures that foster "spiral development" for future system improvements.

Lastly, the ORS standard spacecraft bus should have an operational lifetime of one year.

2.3. ISET Process- Path to Bus Standards

After the first ISET meeting at APL, it was agreed that the ISET would meet in person approximately every 3-4 weeks at either an east or a west coast location. These so-called "Deliberation" sessions, of which seventeen have been conducted to date, were a forum for information gathering presentations. Outside organizations were asked to come and present so that the ISET could build a technical basis to support the standards. Detailed round table discussions were an important part of the process as each member weighed in with their expertise on the wide range of topics discussed. Between the deliberation sessions, a weekly 90-minute teleconference was arranged to update the status of works in progress

To bring a quick focus to the deliberation sessions, the NRL/APL system engineering team formulated a series of topics for initiating trade studies on information gathered in support of the standards development activity. Topic chairs were chosen from the ISET group based on their technical background and interests. The basic requirements used to establish the topic areas were the “external” interfaces for the spacecraft bus and the ability for a single bus to support a wide variety of missions. A brief discussion of each of the topics follows.

2.3.1. Focus Goals, and Accomplishments

The elements critical to the success of a bus standards development effort, the lessons learned from previous bus standards efforts, and the assumptions/goals and products were the subject of this topic. The assumptions and goals were discussed earlier in the paper.

2.3.2. Mission Level Requirements & CONOPS

Given the limited and disparate definitions of tactical, operationally responsive space among the community, it was necessary for the ISET team to define, to a sufficient level of detail, the scope of an entire ORS system (

Figure 2) in order to enable the derivation of requirements for the spacecraft bus. The mission space was broken down into system segments: a facility for rapid integration and testing of the payload to the spacecraft bus as well as the space vehicle to the launch vehicle; the launch and early operations segment; the on-orbit operations segment; and the ground segment, which included the necessary spacecraft bus command and control (C2), as well as the payload C2 and Tasking, Processing, Exploitation and Dissemination (TPED).

The group was also responsible for establishing the seven-day timeline of event from initial needs “call-up,” to final in-theater effects delivery satisfaction. Finally, in conjunction with the group established to consider the resource needs of the payload, an envelope of Low Earth Orbit (LEO), Highly Elliptical Orbits (HEO), and basic “typical” operational scenarios was established.

2.3.3. HEO and LEO Spacecraft

The potential commonality and/or differences in spacecraft bus design between these mission types were covered under this topic. LEO missions launched from the Western and Eastern test ranges were investigated with altitudes from 350 to 705 km. A number of HEO orbits with working apogee altitudes above 7800km were also investigated. These mission types were studied on the basis of differences in both the environmental impacts on bus design and required spacecraft bus subsystem performance.

Since the ORS spacecraft must comply with established satellite disposal procedures, the propulsive capability requirements for LEO and HEO missions were investigated. A drag analysis that reflected represented ballistic coefficients for ORS-class missions was conducted. From the results, it was concluded that for LEO missions with altitudes greater than 600 km, propulsion is required to de-orbit the satellite within the required 25 years. Similarly, for HEO orbits, the directive states that the perigee of a LEO and MEO orbit must be raised to above 2000 km. Since this requires a significant delta V capability, the ORS standard was established to carry enough propulsion to lower the perigee. In addition, the drag environment for LEO missions below 550km required sufficient makeup propulsion to maintain altitude through a nominal year mission life. Given this outcome, the bus standards require some form of propulsion and was one of the modular requirements in the resulting standards.

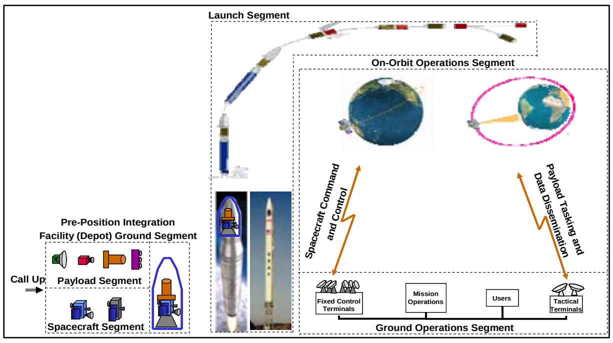

Figure 2: ORS Mission Level Segment Definition

From a radiation perspective, it is not surprising that the HEO orbits define the worst-case charged particle environments. Below 705 km, LEO orbits have a benign conditions. Since spacecraft in HEO orbits spend more time near the orbit apogee, they accumulate a greater dose. At the lower apogees (<3000 km) the environment is dominated by trapped protons and, at the higher apogees, electrons dominate the environment. These results have implication on the radiation tolerance of the spacecraft bus, therefore the standards elected to state the expected environments, as both dose depth curves and particle fluence levels and leave the design mitigation for both Total Ionizing Does (TID) and Single Event Effects (SEE) to the design team based on performance at the design vehicle life.

Table 2: Phase I ORS Bus Characteristics

Requirement Area	Bus Provided Support[1]
Mass	175 kg
Volume	Per mission launch vehicle less 1.6m^3 for spacecraft bus (See Envelope Definition)
Orbit Average Power	200 W
Peak Power	700 W
Orbit Pos. Knowledge	20 m (3σ) combined
Attitude Knowledge	0.017 deg (3σ) each axis
Attitude Control	0.05 deg (3σ) each axis
Slew Rate	2 deg/sec each axis full attitude performance
Spacecraft C2 Downlink Rate	1 Mbps combined bus and payload
Tactical Downlink Rate	UHF typical 9-56 kbps and/or CDL at 274 Mbps (Maximum)
Bus data storage for payload	1 Gbyte (Maximum)

Finally, from a subsystem performance perspective, the relative orbital environments are similar enough to expect that bus performance could be maintained constant between the two mission types, with the exception of communications performance, which would need to be reduced or power aperture increased for the higher propagation distances. The only condition being that the orbital mission operations were properly contained in each mission type.

2.3.4. Payload Support Envelopes

This group was tasked with defining a payload support envelope based on requirements breakpoints that will satisfy a notional "80% solution" to potential ORS missions. Ten missions were identified as requiring LEO orbits. These missions included, space based radar imaging, electro-optical imaging, weather sensing, signals collection, store & forward data ex-filtration and hyper-spectral imaging. Four missions were identified as requiring HEO orbits, including:, communications, blue force tracking, signal collection, and GPS navigation augmentation, were identified as requiring HEO orbits. Two other missions were relatively indifferent to orbit regime, but required very high delta-V requirements and, as such, were not explicitly considered in the final envelope of supported missions.

The performance for each defined mission from both the mission operations perspective as well as the payload support requirements was tracked in a database. In conjunction with the data from the Mission Requirements and CONOPS group, a series of evaluations was performed to capture the performance breakpoints for each payload requirement, to determine what missions may be limited by the 80% solution, and define a recommended payload resources support standard. ***Table 2*** summarizes the payload basic envelope selected standards.

2.3.5. Launch Vehicle Envelopes

This topic reviewed the interface requirements of existing domestically available launch vehicles as well as several currently under development, to derive fairing envelopes, mechanical interfaces, electrical interfaces, and performance requirements for an integrated space vehicle and the spacecraft bus itself. The following options were considered: Space-X Falcon I & V; Orbital Sciences Corporation Pegasus XL, Taurus, and Minotaur IV: SMC Space Test Program Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA); Boeing Delta II & IV dual and secondary payloads; and Lockheed Martin Atlas V dual and secondary payloads.

Table 3, presents a basic "compliance" matrix of the selected launch vehicle interface standards for each of the aforementioned launch vehicles. The ESPA, accommodation was explicitly eliminated from consideration because it was too mass and volumetrically constraining for the ORS type of missions considered. The Pegasus XL was also excluded from deriving any requirements because its performance did not meet most mission types from a mass to meaningful orbit perspective. The Delta II, Delta IV, and Atlas information was also excluded from subsequent requirements because of their cost and non-responsiveness. Emphasis was therefore given to the Space-X Falcon-1, the Minotaur-1 and Minotaur-IV series, and the Taurus launch vehicles.

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[1] At present, the basic envelope defined in ***Table 2*** does not make a performance envelope distinction between mission types. This was a conscious and controversial decision by the ISET team, that in the absence of explicit and compelling analysis, the support and performance envelopes would be kept the same, and the performance and/or operations for any mission would be modified to fit within the envelope.

A bus to launch vehicle mounting definition of a 0.98 m circle with 60 evenly space bolt holes was selected for standardization. To simplify the electrical Spacecraft to launch vehicle interface and keep with the rapid integration, test and launch of the space vehicle philosophy, the space vehicle will be launched powered off. In addition, there will be no spacecraft monitoring after space vehicle fairing encapsulation and no trickle charging of batteries. Thus, the only ground or in-flight connection with the spacecraft will be through redundant loop-back wires that provide the separation indication and power enable functions to the bus.

The topic group also formulated pre-launch and in-flight environments that encompassed the launch vehicle study set.

2.3.6. Bus Functional Decomposition

It is expected that a general and objective analysis of the functional decomposition of the spacecraft bus as applied to the ORS mission space would inform the level and need for the spacecraft modularity. Thus, a functional decomposition, with identified areas of modularity that could allow for targeted spacecraft upgrades without forcing a wholesale redesign of the spacecraft bus is the desired approach. Two approaches were considered for this analysis, a “bottoms-up” approach and a “top-down” approach. From the bottom-up perspective, each subsystem on the spacecraft was evaluated among a number of conditions to assess how modular, or what the tendency was for the subsystem to change either due to performance and/or obsolescence. The “top-down” approach considered the performance needs of the missions identified to determine the areas where the spacecraft bus could be “optimized” to support a specific mission.

From both perspectives, the analysis performed suggests that the spacecraft bus can indeed be considered to have a "core" platform, unique to specific manufacture design approach for the command and data handling computer processing, harnessing, thermal control, power management, power distribution and structural design. Elements of the spacecraft bus that could be “modularized” were found to include the payload, electrical power generation, electrical power storage, data storage, attitude knowledge components, attitude actuator components flight software architecture, and the RF communications and propulsion. These conclusions are consistent with several other ongoing efforts, such as the AFRL PnPSat program.

Given the current state of the bus standards and the general “spiral” philosophy, the recommendations regarding bus functional decomposition and degree of spacecraft modularity was limited at this time to just the payload, propulsion system, battery, and a tactical RF Communications link.

2.3.7. Test and Verification Approaches

The focus of this topic was identification and preliminary development of a cost effective test and verification approach for multiple-spacecraft builds that would enable minimal cycle time from call-up through on-orbit checkout. The expertise of the team members from the production runs of the Iridium and Globalstar constellations was invaluable to this activity. The basic test flow and philosophy was established for the rapid integration of spacecraft bus to payload, and then the space vehicle to launch vehicle. This evoked the need for high-level “embedded” built-in-test capabilities for the spacecraft bus and payload, as well as standardized interfaces/connectivity to common ground test equipment.

2.3.8. Communications Interfaces

A key external interface for the space segment (bus and payload) is RF communications to the ground. This topic investigated standardization for spacecraft command and control communications link and the tactical communication link. ***Figure 4*** presents a basic high-level view of the RF communications pathways envisioned in the standards. Other issues that were investigated related to both current and future approaches that the military is planning for RF Communications including, data flow, frequency band definitions, modulation techniques, data rates, communication security (COMSEC) and basic definition of ground interface locations were investigated. Given the current maturity of the general military spacecraft command and control network, the present SGLS architecture and the expected Unified S-Band (USB) architecture were established as the standard. For the tactical links, standard UHF was established for low data rate application, and the Common Data Link (CDL) protocol was recently established as the high data rate standard.

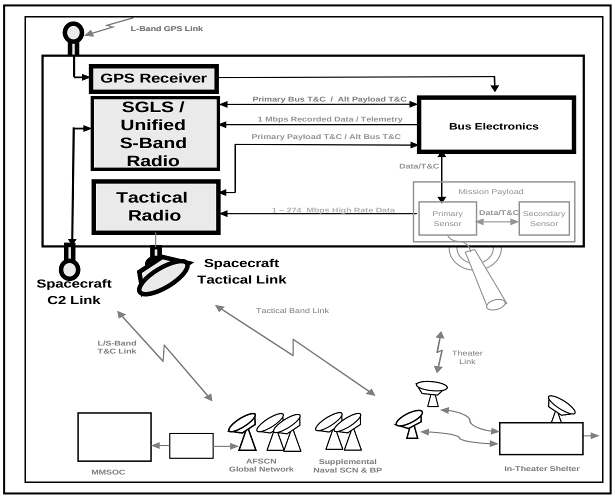


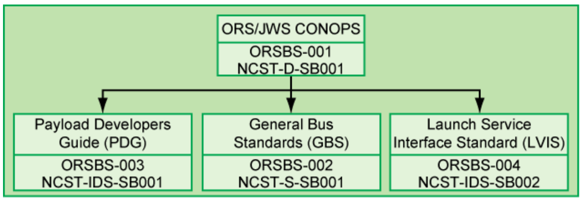
Figure 3: RF Communications Architecture

2.3.9. Ground Support Checkout Interface

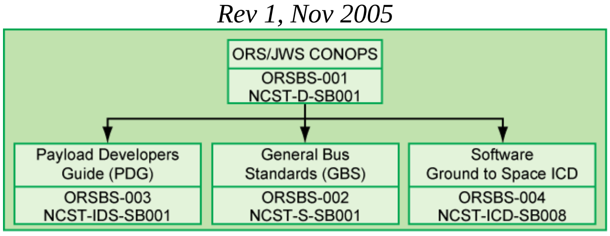
In support of the rapid call-up scenario, standards for interfacing spacecraft bus and the payload, and processing the integrated space vehicle though launch, is one of the unique activities under the ISET derived ORS system design. The need to develop an approach for this effort in sufficient detail in order to derive requirements that would influence the spacecraft bus design is critical. The approaches developed have design and manufacturing ramification on the bus, such as the ability to install batteries late in the flow, rapid "built-in-test" capabilities, periodic checks, and access and safety implications[2].

2.4. ISET Products – Bus Standards

The first revision of the ISET Standards released were four documents, *Figure 4* presents a basic flow down between and among this document set.



Rev 1, Nov 2005



Rev 3, Feb 2008

Figure 4: ORS Bus Standards Document Structure

The Business Team developed the "ORS Bus Standards Transition Plan" which puts the ISET technical documents in the context for transition into acquisition. This Transition Plan recommends an approach for maintaining standards, for phased procurements and for programmatics. This plan provides cost estimates as well as examples and approaches from similar markets.

2.4.1. Mission Requirements and CONOPS

This document represents a top-level definition of the overall ORS mission, as defined by the ISET. The primary focus of this document was to investigate the orbital environments, envelope the multi-mission support requirements, establish to the extent possible concepts for tactical support and define concepts for operational responsiveness, and develop scenarios. Based on these assumptions, the system can be broken down into segments, with the corresponding document defining the scope of the standards in each segment. It presents the basic CONOPS timelines (*Figure 5*) for asset call up, integration, launch and on-orbit operations. It also discusses basic mission definitions, assumptions with which these standards are based and the evolution from the Phase I efforts.

The ORS system is intended to provide responsive launch upon demand to support tactical needs by the Warfighter. In order to achieve the modularity and responsiveness envisioned for an ORS capability, the procurement agency would develop standardized interfaces between and potentially within, the busses, payloads, and launch vehicles. In order to achieve the cost efficiencies desired, bus, payload, and booster design would remain constant allowing for multi-year block purchases with spiral changes for new technology insertion at regular intervals. The envisioned System Architecture is shown in *Figure 6*.

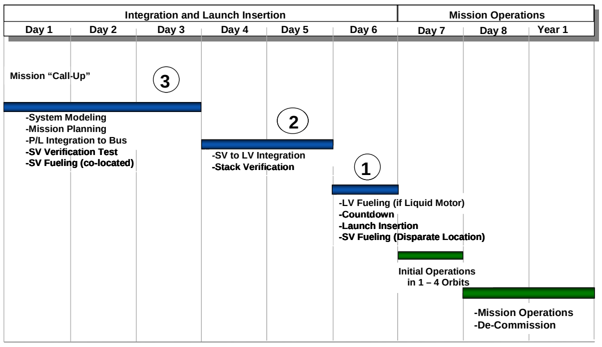


Figure 5: Top-level Timeline

The ISET assumptions are aligned along the Tier 2 of the Tiered approach of ORS goals. Future activities for refining this document will be done at the direction of the ORS Office.

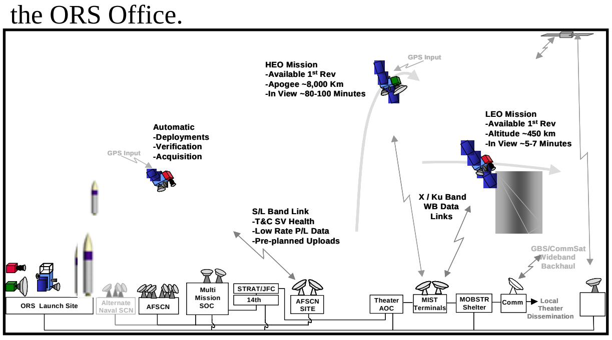


Figure 6: System Architecture

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[2] In development of these requirements, for the bus, a number of requirements for the design and development for the "integration facility/depot" itself were identified and are included in the standards as reference material to inform future development activities.

2.4.2. General Bus Standards Document

This document contains general programmatic requirements for interactions of the vehicle manufacturer with the government, RF communications interfaces, interfaces with the ground operators for the spacecraft command and control (C2), bus functional and performance requirements, ground support equipment and integration facility requirements, and mission/quality assurance provisions. The capabilities and the requirements for the design, development, manufacturing and testing of a spacecraft bus to support a class of ORS mission are captured. It identifies the necessary performance requirements, interface definitions, and general ORS philosophies needed by mission designers and spacecraft bus manufactures to be compatible with other segments of the overall ORS system (e.g., launch vehicles, payloads, etc.). There are many performance requirements that the spacecraft bus must meet which are contained in the ORS Payload Developers Guide (ORSBS-003) and Software ICD (ORSBS-004). These two documents in combination with this document represent a complete set of technical requirements for the spacecraft bus.

In developing the bus requirements, the ISET focused on a functional decomposition analysis of the spacecraft bus to investigate and promote present and future modularity without dictating any specific implementation. It was decided that significant bus modularity and standardization at the subsystem level is currently impractical for a six-day integration process at the SVIF facility. The benefit to subsystem modularity benefit is realized within the bus fabricator facilities, by reducing cost and schedule and by creating an open component market that allows increased competition. It is also believed that, if standards are not pushed to subsystem interface levels, nothing new or revolutionary has been achieved.

This document also defines, in sufficient detail, the interfaces of the spacecraft bus to a generic ORS Launch Vehicle. No additional LV information would be needed for a spacecraft manufacturer to build a spacecraft bus to fly in the ORS system. This document is also an interface control document from the LV perspective. It includes Pre- and Powered-flight environments and all interfaces (mechanical, electrical, thermal, etc.)

The General Bus Standards document is to be used as the sole input for development of busses to the ORS Standards. This document covers all aspects of the launch vehicle interface, launch site processing, and mission design associated with launching spacecraft built to the Standards. This document is to be used to directly or indirectly derive information and requirements needed to further the design of spacecraft busses through the Critical Design Review (CDR) phase of the mission. This document shall stay in effect throughout the development of the spacecraft bus.

Table 3 summarizes the space vehicle (integrated bus built to the standards and an ORS payload) compatibility with various launch vehicles if the Bus Standards are followed.

Table 3: Summary of Launch Vehicle Compatibility

	ESPA	Pegasus	Taurus	Minotaur I	Minotaur IV	Space-X Falcon 1	Space-X Falcon 5	Delta II, IV	Atlas V	DARPA FALCONs
Mass & CG	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Envelope	No	No	Yes	Yes, for larger fairing	Yes	Yes	Yes	Yes, except dual PL height	Yes, except dual PL height	Yes
Mounting	No	Yes	Yes	Yes	Yes	Yes	Can conform	Can conform	Can conform	Yes
Electrical	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quasi Static Loads	No	Yes	Yes	Needs Load Isolation	Needs Load Isolation	Yes	Not Yet Specified	Yes	Yes	Yes
Random Vibe	Not Yet Specified	Needs Load Isolation	Covered by Acoustics	Yes	Covered by Acoustics	Yes	Not Yet Specified	None Specified	None Specified	Covered by Acoustics
Sine Vibe	Not Yet Specified	None Specified	Needs Load Isolation	None Specified	Yes	None Specified	Not Yet Specified	No, need analysis	No, need analysis	None Specified
Acoustics	Yes	Yes	Yes	Yes	Yes	Yes	Not Yet Specified	Yes	Yes	Yes
Shock	Yes	Yes	Yes	Yes	Yes	Yes	Not Yet Specified	Not usually a driver	Not usually a driver	Yes
Pressure	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Thermal	Yes	Not usually a driver	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Safety	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

2.4.3. Payload Developers Guide

This document presents the envelope of capabilities and the requirements for support of the selected range of potential missions. It identifies the necessary performance requirements, interface definitions, and general ORS philosophies needed by mission designers and payload developers to be compatible with the ORS spacecraft bus and launch capability. The Payload Developers Guide (PDG) is intended to be a standalone document from the payload provider's perspective

The support accommodations for the PL contained within this document was derived from an enveloping process conducted by the ISET In order to develop effective standards, it was necessary for the ISET to research the mission needs and PL support requirements across a wide range of potential missions that were representative of a typical mission for the ORS program. *Table 4* shows the capabilities available to a potential payload. The volume available to the Payload is shown in *Figure 7*.

A description of the range of missions reviewed and the resulting data set for each mission is contained in the ORS Mission Requirements and Concept of Operations document, the support level results are summarized in *Table 5*. The requirements in the table are the maximum potential requested support levels for each type of mission, and where payload envelope levels have been chosen at less than the mission's maximum level, smaller or less aggressive missions of the same type may be supportable by the standard capabilities.

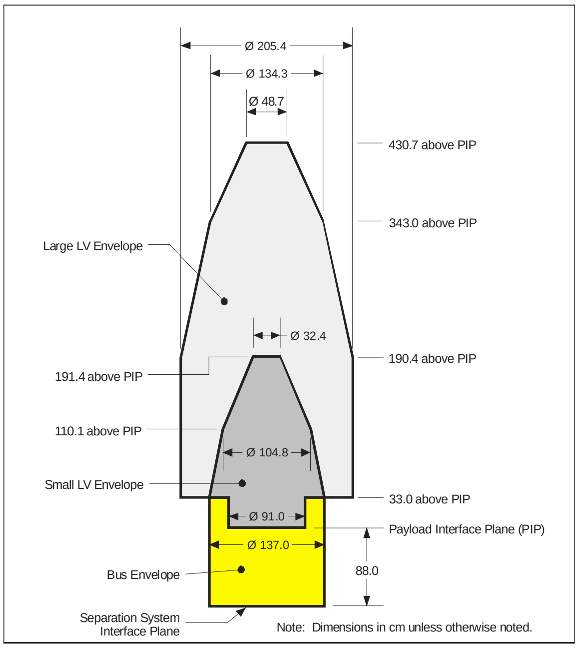

Figure 7: PL Stowed Envelope

It is important to note this document is not a complete design standard for the payload itself; it only covers the interfaces and support accommodations with the spacecraft bus and launch support service. There are many aspects of the payload design that are dependent on the actual mission the payload is intended to fulfill, thus many requirements and specifications that would be found in a payload design specification would need to be provided by the specific payload procurement agency.

Table 4: Supported Payload Capabilities

PL Support Item	Selected Capability	Comments
Mass [kg]	200	Captures 87% of maximums
Volume [m^3]	(see *Figure 7*)	LV fairing constraints to be used
Orbit Average Power [W]	200	Captures 94% of maximums
Peak Power [W]	700	Captures 81% of maximums
Orbit Position Knowledge-3σ [m]	90	Captures 81% of maximums
Attitude Knowledge-3σ [deg]	1 arc-min at I/F	Captures 75% of maximums
Attitude Control-3σ [deg]	0.05	Captures 81% of maximums
Slew Rate [deg./sec]	2.0	Captures 87% of maximums
S/C SB Ops Data Rate [Mbps]	5	Captures 100% of maximums
Tactical D/L Data Rate [Mbps]	274*	*As state-of-the-art permits
PL Data Storage [GB]	0	Spacecraft will store only state-of-health data
Thermal Dissipation to SB [W]	60	PL brings any extra radiator

2.4.4. Data Interfaces: Bus to Payload & Ground

This document defines the data exchange protocols, data transport formats, packet definitions and field definitions for the Bus/Payload interface. Underlying electrical interface for the Bus/Payload interface is the HDLC and SpaceWire. The Bus/Payload interface is defined such that the HDLC interface, Spacewire interface, or both can be utilized. The Bus design will provide support for both interfaces. The Payload may choose to implement either one or both. The Bus/Payload Interface is defined to dynamically support either or both interfaces without the need for Bus reconfiguration (i.e. FSW changes).

Table 5: Mission Set

Mission / Orbit Class	Selected Level	RADAR: LEO Theater Single Target	Electro-Optical - LEO Imaging (Single Target)	Signal Collection - LEO Global	Electro-Optical - LEO Push Broom	Electro-Optical - LEO Imaging (mosaic)	Weather Sensing	RADAR: LEO Theater Single Target	Hyper-Spectral: LEO Push-Broom Earth Mapper	Hyper-Spectral: TacSat 3	Hyper-Spectral: LEO Target Imager (mosaic)	Blue Force: HEO Long Dwell	Signal Collection - - HEO	Navigation (GPS): HEO Theater Long Dwell	Comm - HEO Theater Long Dwell	Space Surveillance: LEO Maneuverable	Space Control - LEO Maneuverable
Mass	200 kg	100	117	100	120	171	200	75	250	200	250	92	125	168.2	200	200	200
PL-OAP (Payload Orbit Average)	200	14		40			100		250		250	200	75	217	350	100	250
Peak Power during Collect	700 w	40	58	115	135	345	400	700	700	190	1000	200	215	250	500	200	1000
Knowledge Accuracy (3-σ)	0.01 deg		0.05	0.1		0.003	0.03	0.02	0.05	0.002	0.005	0.05	0.1	1.6	0.01	0.005	0.01
Pointing Accuracy (3-σ)	0.05 deg	0.1	0.1	0.25	0.25	0.03	1	2	0.5	0.03	0.05	0.5	0.25	1	0.1	0.05	0.1
Slew rate	2 deg/sec		1	2		4	0.1	1.00	1	3	1	2	2	2	2	1	2
Data Storage Req'd	0 GB	20	0.8	8	20	16	1	100	2	16	2	0.1	4	0		60	20
Low rate DL	2000 kbps	1000	2000				128	64	64	2000	64	200		16		100	64
High-rate D/L	274 Mbps		274	45	110	110	0	270	30	548	30		2	0	45		274
Dissipation during Collect	TBD W			65	130	345	400	1000	500	500	500		115	250		150	
Orbit Knowledge	20 m	20	20	20	20	10	20	20	20	10	10	20	20	20	20	20	20

This document also defines the data exchange protocols, data transport and packet template for the Space/Ground interface. The Space/Ground Interface definition assumes the use of a flight side SGLS transponder integrated with COMSEC slices. The SGLS forward link assumes a flight-side Cardholder COMSEC slice. The SGLS return link assumes that the SGLS transponder supports both the narrow-band and wide-band interfaces. While a return link COMSEC is required, this document assumes that the return link COMSEC does not levy any blocking or packaging constraints for the return link. This interface standard was developed as part of the ORS Phase 3 Bus effort. This interface standard was adopted by the ORS Phase 3 Bus and COMMx payload elements. As a result, the TACSAT-4 spacecraft implemented the enclosed interface standards for its Bus/Payload and Space/Ground interfaces.

This document is limited to and currently defines the interfaces between the spacecraft bus and the payload, and between the spacecraft bus and the ground. Subsequent releases will define the additional internal interfaces. The depth of detail required for interface standardization and the need for coverage of additional interfaces is an ongoing assessment effort by ORS supported standards definition efforts. The intent is to levy interface standards where these standards will lead to efficient system integration, robust operational capabilities, and improved system flexibility while reducing overall system cost.

3. TACSAT4 IMPLEMENTATION

The initial set of standards (Rev 0) was released by the ISET in Nov 2005, at which point a separate NRL/APL team was given these standards and tasked, to the extent possible, with developing a compliant bus design. The actual mission that this spacecraft bus was to support was not defined, however, it should have the capability to support any of the identified missions (*Table 5*). The design as presented at the ORS Phase III CoDR based strictly on the standards. At the CoDR, it was evident that the Phase III Bus standards as written, were not achievable for this class of spacecraft. The initial concept for the Bus came in at 431 kg vs. the 200 kg envisioned by the ISET.

A red team review of the standards and implementation revealed a couple areas that compounded the problems. The power subsystem mass estimate was 3+ times allocation and was driven by design for worst case eclipse conditions and an ACS load motivated by reaction wheels capable of 2+ degrees/sec for unrealistic inertias—most notably 300 m/sec delta V, and system mass estimates with a margin of 75 kg when the S/C bus not to exceed target was 200 kg. Changes were made to the standards such that the "80%" rule was enforced, and in the case of delta V, reduced to a more manageable number. Delta V was reduced to 175 m/sec or less depending on final system mass. Reaction wheel sizes were reduced such that, depending on the payload flown, from 2 degrees/second is achievable. These two items, along with review of the power implementation, resulted in a dramatic reduction in EPS system mass. For example, the required battery at CoDR was presented as 110 amp-hrs, was subsequently reduced to 50 amp-hrs, with a final implementation of 30 amp-hrs, which will meet the majority of the missions investigated. Additionally, the system mass margin was reduced to minimal numbers, which were much more manageable.

A critical aspect of the relationship between the prototype bus implementation team and the ISET bus standards effort is the manner in which the process was managed. Specifically, the bus implementation team baselined (Baseline Rev 1b) a Preliminary Design Review (PDR) set of ISET standards and interfaces to provide a consistent means of comparison throughout the life of the program. It was known, however, that many issues were still unresolved at that particular time and that additional standards/interface development continued often incorporating information from the bus prototype build. As the ISET continued maturing the standards, the prototype bus implementation team provided inputs and technical responses to ISET queries, but new or refined ISET standards were not imposed on the bus implementation team. Thus, the bus implementation team was able to inform the ISET efforts but was not required to react to a continuous flow of changes and considerations generated by the ISET at PDR. This resulted in the progression of the prototype bus implementation towards completion while at the same time produced a more complete and informed set of released ISET standards. The process is represented in
Figure 8.

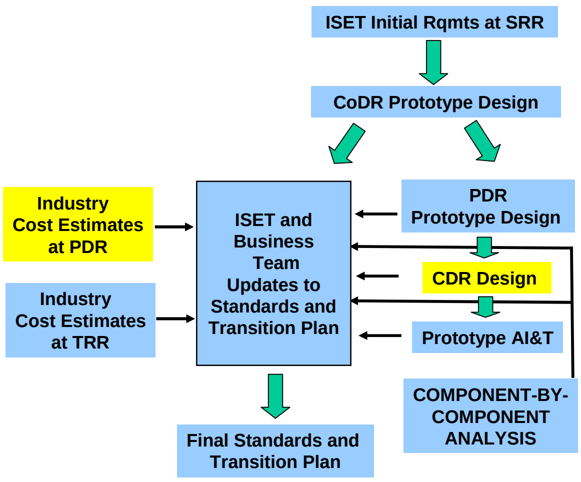

Figure 8: Phase III Implementation

3.1. Implementation Requirements

The additional requirements to meet the TACSAT- 4 mission were also added to the bus requirements. Furthermore, some of the initial constraints on the ORS CONOPS were modified, as it became evident that for HEO mission ISET needed to also envelope the 4-hour orbit. The Minotaur IV as baselined for the standards development does not have sufficient capability to deliver the system to the objective 4 hour HEO orbit, therefore a Minotaur IV Plus option is now under development by the Responsive space launch Program.

A separate document, the Implementation Payload developer's guide was written, which encompasses the implemented requirements vis-à-vis those levied upon the spacecraft bus and the COMM-x payload. During the initial phase of the prototype bus development each subsystem has had to work with two sets of requirements: the ORS Phase III Standards and the TacSat-4 mission requirements. At the bus preliminary design review, each subsystem lead had determined the Standards Requirement that will be implemented and derived subsystem level requirements. Since the ISET had not yet addressed the entire payload to bus interfaces, the bus team determined if additional requirements were needed at the spacecraft/standards level to complete the prototype design. These additional requirements were categorized in two ways: (1) standards requirement, recommended (or not) for incorporation into the ISET standards and (2) COMM-x mission specific requirements.

The resulting prototype bus requirements flowed down from the ISET derived ORS bus standards with identified excursions for the TacSat-4 mission, the Minotaur-IV with Star 48BV launch vehicle, and the Comm-X payload. Each subsystem lead engineer was responsible for identifying all ISET standards that could be validated at the subsystem level within programmatic constraints and then deriving any additional requirements to meet mission or payload requirements. Feedback to the ISET was provided at external reviews and deliberation sessions where baselined standards were felt to be missing or in need of refinement.

In general, ISET standards related to quantity builds (such as I&T flow, production, etc) as well as requirements related to storage/depot operations are not validated because they are not applicable to a single prototype build.. ISET defined interfaces were ranked in terms of importance relative to efforts to validate standards, with the bus to payload and bus to launch vehicle interfaces being selected as the most critical.
The general flow of requirements, including general ISET derived requirements and specific mission/payload implementation requirements appears in *Figure 9*.

3.2. Phase III Prototype Completion and Use

The prototype build of the ORS Phase III spacecraft bus was completed on April 25, 2008. The spacecraft will be in storage until late summer. TacSat-4's COMMx payload is expected to be complete by late summer 2008 and will be mated with the bus. The integrated space vehicle will undergo, EMI/EMC, and Magnetic dipole system level testing. Once the Space Vehicle level testing is complete, the spacecraft and payload will be in storage until July 2009. Current plans are for launch from the Kodiak, Alaska range on-board a Minotaur –IV Plus in September 2009, into a critically inclined, highly elliptical 700km x 12050km orbit.

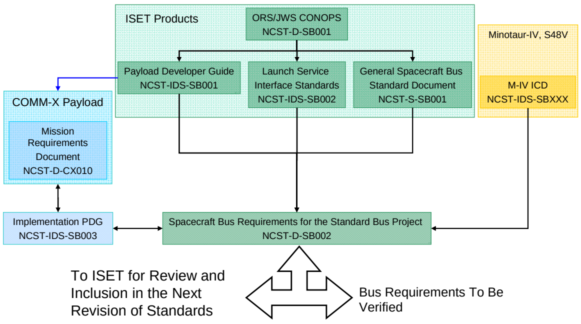

Figure 9: Requirements Flow

4. CONCLUSION

Through the efforts of the Integrated System Engineering Team and the associate prototype teams, the program has successfully produced an extensive and well-documented set of ORS Bus Standards consistent with the ORS CONOPS and classes of missions. The process used to produce these standards has resulted in technically sound standards which are understood and "bought into" by industry. Business factors were also strongly considered to improve the transition of these standard into successful acquisition under a subsequent operational phase. While ORS must provide the business foundation, these technical standards are intended to be more broadly useful in order to further volume production, standards acceptance, and the industry business cases.

5. ACKNOWLEDGEMENT

The authors would like to recognize the contributions of the ISET team, the information contained in the standards and this document is a consolidated summary of 3 years of work by the team. The authors are grateful to: Mr. Bob Summers formerly from AeroAstro, Inc.; Mr. Paul Tarbuck from Boeing; Mr. Gerry Murphy from Design_Net Engineering; Mr. Bob Smith from General Dynamics-Spectrum Astro; Dr. Walter Gelon from Space Systems Loral; Dr. Kirk Stewart and Mr. Paul Graven from Microcosm; Mr. Jeff Summers from MicroSat Systems, Inc.; Mr. Larry Slivinski and Ms. Deborah Westley from Orbital Sciences; Dr. Allan Mense and Mr. Chuck McMullin from Raytheon; Mr. Blake Crowther and Mr. Jim Dyer from the Space Dynamics Laboratory, and Mr. Jeff Baker and Mr. Robert Meurer from Swales (now ATK). The information specific to the development of the Bus prototype is result of efforts of the NRL and the JHU/APL bus implementation team.

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